

The Importance of Shocks in the Ionization of the Narrow Line Region of Seyferts

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Abstract.

We discuss the viability of shocks as the principal source of ionization for the Narrow Line Region of Seyfert galaxies. We present the preliminary results of [OIII] λ 5007Å and radio 3.6 cm imaging surveys of Seyferts, discuss the effects of shocks in the ionization of two galaxies, and also calculate an upper limit to the H β luminosity that can be due to shocks in 36 galaxies with unresolved radio emission. We show that, for favored values of the shock parameters, that shocks cannot contribute more than $\sim 15\%$ of the ionizing photons in most galaxies.

1. Introduction

The close connection between the narrow line and the radio emission in Seyfert galaxies is a well known fact. The first papers in this subject found a correlation between the [OIII] and radio luminosities, and between the radio luminosity and the FWHM of the [OIII] lines (DeBruyn & Wilson 1978, Heckman et al. 1981, Whittle 1985). Emission line and radio imaging of Seyfert galaxies shows that the radio and line emission of these galaxies is aligned (Haniff et al. 1988). Higher resolution imaging shows, for some of these galaxies, that the radio emission is surrounded by line emission (Pogge & De Robertis 1995, Capetti et al. 1996, Falcke et al. 1998), which suggests that the Narrow Line Region gas (NLR) is ionized by shocks due to the interaction of the radio plasma with the gas (see Figure 1 for an example). Another evidence of shocks in the NLR of Seyferts

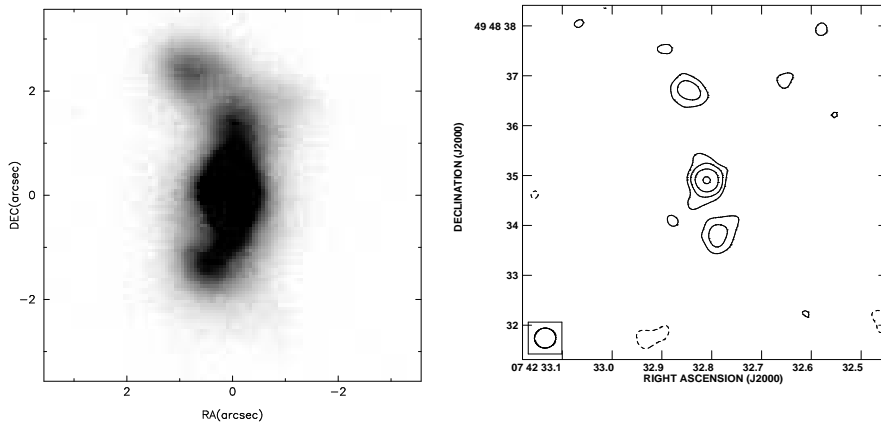


Figure 1. Comparison of the CFHT [OIII] λ 5007Å image of Mrk 79 (left) with the VLA A-conf. 3.6 cm image (right), on the same scale.

is the detection of anomalous velocity fields, like double components separated by hundreds of km/s (Whittle et al. 1988, Winge et al. 1997, Hutchings et al. 1998), and “extra” line widths associated with radio jets (Whittle 1992).

These results lead Dopita & Sutherland (1995, 1996) to propose a series of models where the NLR is ionized by fast shocks, with velocities in the range $150 \leq V_{shock} \leq 500$ km/s. According to their models, high energy photons are created behind the shock and ionize the preshock gas upstream (precursor). This model has several predictions, which were analyzed by Morse et al. (1996) and Wilson (1997), and are summarized below. The models predict we should find line emission surrounding radio lobes, and a photon deficit in the NLR. However, this can also be explained by the Unified Model (see Young et al. 2001 for a discussion on X-ray results). Shocks can explain the [OIII] temperature problem in these galaxies, where the measured gas temperature is much higher than the one predicted by simple photoionization models, but this can also be explained combining matter bounded and ionization bounded clouds (Binette et al. 1996).

Here we present the preliminary results of a radio and [OIII] λ 5007Å imaging survey of a sample of Seyfert galaxies. We discuss the case of two individual galaxies and calculate a limit to the $H\beta$ luminosity that can be due to shocks in those galaxies without extended radio emission.

2. Radio and [OIII] survey of Seyfert galaxies

Our radio continuum survey was done using the VLA in A-configuration at 3.6 cm, which gives a resolution of $0.25''$. The results of this survey were published by Kinney et al. (2000) and Schmitt et al. (2001). The [OIII] survey is underway. It started with the CFHT and is now being done with HST.

One of the results from the radio continuum survey is that only 50% of the Seyferts show extended emission. This percentage decreases to 25% if we count only those galaxies where the radio emission is composed of multiple components. Comparing the radio and [OIII] images we find some interesting

cases, like NGC5347 (Figure 2). This Figure shows that the [OIII] emission is resolved, but the radio emission is unresolved, contrary to what would be expected if shocks were important in the ionization of the NLR of this galaxy. On the other hand we also have cases like Mrk 79 (Figure 1), where both the [OIII] and radio emission are extended and cospatial, suggesting that shocks may be an important source of ionizing photon. We discuss these galaxies below.

We will use in the following subsections the equations given by Dopita & Sutherland (1996) to predict the $H\beta$ luminosity produced by a shock and the precursor, which are, respectively,

$$L(H\beta) = 7.44 \times 10^{-6} A (V_s/100 \text{ km s}^{-1})^{2.41} (n/\text{cm}^{-3}) \text{ erg s}^{-1}$$

$$L(H\beta) = 9.85 \times 10^{-6} A (V_s/100 \text{ km s}^{-1})^{2.28} (n/\text{cm}^{-3}) \text{ erg s}^{-1}$$

where A is the shock area, V_s is the shock velocity and n is the preshock density.

2.1. NGC5347

This is a Seyfert 2 galaxy with a radial velocity of 2335 km s^{-1} , so $1''$ corresponds to 150 parsecs at the galaxy (we assume $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$). As we can see in Figure 2, the [OIII] image is extended, with a cone shaped structure in the circumnuclear region. At $\approx 3''$ NE from the nucleus we can see [OIII] emission detached from the nuclear emission (NE structure), with a total linear extent of $2''$. The borders of this structure are well aligned with the borders of the cone structure at the nucleus, suggesting that the NLR is ionized by the nuclear source, and the collimation of the radiation is due to a circumnuclear torus. Figure 2 also shows the archival VLA 6 cm image of this galaxy, which is unresolved. The radio emission is unresolved at 3.6 cm, 6 cm and 20 cm, indicating that we did not resolve out diffuse emission around the nucleus. In fact, the comparison between the 20 cm flux from the nuclear source (3.4 mJy) with that from the entire galaxy (5.6 mJy), obtained from the NVSS, shows that most of the radio emission in this galaxy originates in the nuclear region.

Here we calculate how much of the $H\beta$ emission from the NE structure can be due to shocks. If we assume that the $H\beta$ flux is produced by a shock seen edge-on, with a circular cross section of radius $1''$, we get that the shock area is 0.071 kpc^2 ($6.75 \times 10^{41} \text{ cm}^2$). González Delgado & Pérez (1996) obtained spectra of this galaxy and showed that the NE structure has $L(H\beta) = 2 \times 10^{39} \text{ erg s}^{-1}$, $[OIII]/H\beta = 7.6$, $n_e = 350 \text{ cm}^{-3}$, and the $\text{FWHM}([OIII]) = 80 \text{ km s}^{-1}$. According to Ferruit et al. (1999), the pre-shock density for a shock with this velocity would be of the order of $n = 15 \text{ cm}^{-3}$. Using the equations given above, for a shock of velocity $V_s = 100 \text{ km s}^{-1}$ and preshock density $n = 15 \text{ cm}^{-3}$, we get $L(H\beta) = 7.5 \times 10^{37} \text{ erg s}^{-1}$ and $L(H\beta) = 1.0 \times 10^{38} \text{ erg s}^{-1}$ for the shock and precursor, respectively. This corresponds to $\approx 10\%$ of the observed $H\beta$ luminosity. Another problem with the shock ionization of the NE structure is that the $[OIII]/H\beta$ ratio can only be reproduced with a shock of 400 km s^{-1} , which is inconsistent with the observed FWHM of the [OIII] line.

We now use this same approach for the nuclear region of this galaxy. According to González Delgado & Pérez (1996), the nuclear spectrum has $L(H\beta) = 1.0 \times 10^{40} \text{ erg s}^{-1}$ and $n_e = 400 \text{ cm}^{-3}$. They also found that the [OIII] line can be decomposed into a narrow and a broad component, with the broad component having $\text{FWHM}([OIII]) = 500 \text{ km s}^{-1}$. Again, if we assume that we are

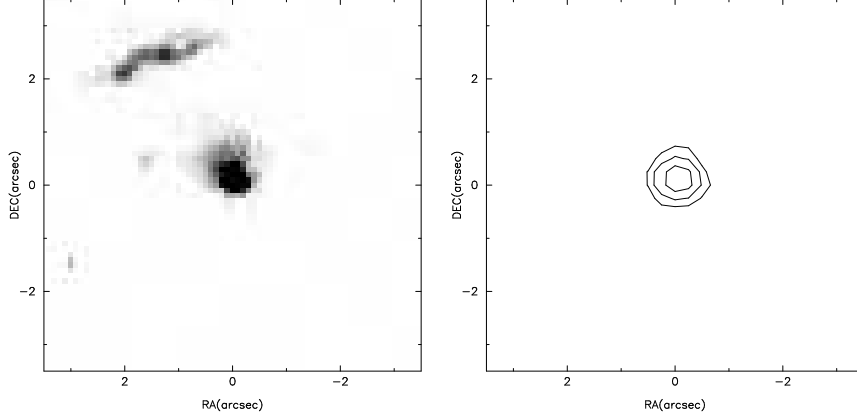


Figure 2. Comparison between the HST [OIII] $\lambda 5007\text{\AA}$ images of NGC 5347 (left) with the archival VLA A-config. 6 cm image (right).

seeing the shock edge-on, with a circular cross section of radius $0.5''$, we get that the shock area is 0.018 kpc^2 ($1.7 \times 10^{41} \text{ cm}^2$). We get that for a shock velocity $V_s = 500 \text{ km s}^{-1}$ and a preshock density $n = 10 \text{ cm}^{-3}$, $L(\text{H}\beta) = 6.3 \times 10^{38} \text{ erg s}^{-1}$ for the shock and $6.6 \times 10^{38} \text{ erg s}^{-1}$ for the precursor, which corresponds to $\approx 10\%$ of the observed $\text{H}\beta$ luminosity. These results indicate that shocks are not extremely important for the ionization of the NLR of this galaxy.

2.2. Mrk 79

The [OIII] and radio images of Mrk 79 are shown in Figure 1. This Figure shows that the [OIII] emission of this Seyfert 1 galaxy is extended by $\approx 5''$ along the N-S direction. The radio emission lies along the same direction, but is extended by only $\approx 3''$. The radio structures to the N and S of the nucleus are surrounded by the [OIII] emission, suggesting that shocks may play an important role in the ionization of the gas. Using the same technique used for NGC5347, we calculate what would be the contribution of shocks to the $\text{H}\beta$ luminosity of the N and S regions of the NLR. We assume the shocks have a circular cross section of radius $0.5''$, which corresponds to an area of 0.145 kpc^2 ($1.4 \times 10^{42} \text{ cm}^2$), considering the galaxy has a radial velocity of 6643 km s^{-1} . From Whittle et al. (1988) we have that the N and S lobes have $\text{FWHM}([\text{OIII}]) = 400 \text{ km s}^{-1}$ and 350 km s^{-1} , respectively, which we assume to be the shock velocities. Assuming a preshock density $n = 10 \text{ cm}^{-3}$, we can calculate that the sum of the shock and precursor $\text{H}\beta$ luminosities are $6.1 \times 10^{39} \text{ erg s}^{-1}$ for the N component, and $4.5 \times 10^{39} \text{ erg s}^{-1}$ for the S component. Using our CFHT $\text{H}\alpha$ image and assuming $\text{H}\alpha/\text{H}\beta = 3.1$, we get the observed $L(\text{H}\beta) = 2.8 \times 10^{40} \text{ erg s}^{-1}$ and $1.9 \times 10^{40} \text{ erg s}^{-1}$ for the N and S components, respectively. This means that $\approx 25\%$ of the photons ionizing the N and S lobes of this galaxy can be due to shocks.

2.3. Seyferts with unresolved radio emission

Another test of the importance of shocks to the ionization of the NLR of Seyferts was done using those galaxies for which we do not observe extended radio emis-

sion. We use the same method used for NGC5347 and Mrk 79. Since these galaxies are unresolved in radio, we make the conservative assumption that the shock has a circular cross section with radius $0.25''$, two times larger than the resolution of the observations. We do not have information about the $\text{FWHM}([\text{OIII}])$ of these galaxies, so we assume that all the galaxies have shocks of 500 km s^{-1} , at the high end of the parameters modeled by Dopita & Sutherland (1995, 1996), and use a preshock density of $n = 10 \text{ cm}^{-3}$. Given these assumptions, we should consider these results as upper limits to the contribution of shocks to the ionization of these NLR's.

Table 1. Observed and predicted $\text{H}\beta$ luminosities¹

Name	L($\text{H}\beta$) Obs	L($\text{H}\beta$) Calc	Ref.	Name	L($\text{H}\beta$) Obs	L($\text{H}\beta$) Calc	Ref.
Mrk 1	16.55	1.34	1	I 01475-0740	5.99	1.65	1
Mrk 1040	7.24	1.42	2	UGC 2024	6.72	2.64	1
MCG -2-8-39	20.13	4.61	1	I 03125-0254	10.93	3.03	1
Mrk 607	2.20	0.43	1	I 04385-0828	1.27	1.20	1
MCG -5-13-17	3.37	0.84	3	UGC 3478	1.87	0.86	1
UGC 4155	26.14	3.42	1	Mrk 1239	39.53	2.09	3
NGC 3783	4.99	0.38	4	NGC 4593	10.23	0.43	5
NGC 4704	8.46	3.87	1	MCG -2-33-34	19.67	1.13	3
I 13059-2407	1.49	1.02	1	MCG -6-30-15	1.10	0.32	6
NGC 5347	12.00	1.47	11	I 14434+2714	31.44	4.54	1
UGC 9826	8.49	4.48	1	I 15480-0344	10.55	4.83	1
I 16288+3929	26.41	4.83	1	I 16382-0613	11.64	4.05	1
UGC 10889	7.56	4.15	1	MCG +3-45-3	30.58	3.11	1
UGC 11630	1.22	0.78	1	NGC 7213	3.69	0.19	7
Mrk 915	35.63	3.06	2	UGC 12138	16.22	3.18	1
UGC 12348	26.96	3.37	1	Mrk 590	22.66	3.66	8
Mrk 1058	1.74	1.54	2	Mrk 705	19.16	4.39	9
UGC 6100	39.39	4.51	9	UGC 10683 B	6.54	4.99	10

¹Luminosities are in units of $10^{39} \text{ erg s}^{-1}$. The $\text{H}\beta$ luminosities calculated based on shock models include both the shock and the precursor. References: (1) de Grijp et al. (1992); (2) Dahari & De Robertis (1988); (3) Rodríguez-Ardila et al. (2000); (4) Winge et al. (1992); (5) Clavel et al. (1983); (6) Reynolds et al. (1997); (7) Filippenko et al. (1988); (8) Stirpe (1990); (9) Cruz-Gonzalez et al. (1994); (10) Wilson et al. (1981); (11) González Delgado & Pérez (1996).

We show in Table 1 the observed and calculated (shock+precursor) $\text{H}\beta$ luminosities of the galaxies with unresolved radio emission, as well as the references from which we obtained the observed values. On average only 15% of the observed $\text{H}\beta$ luminosity can be due to shocks, and this number is likely to be smaller, given the favorable shock parameters we assumed.

3. Summary

We presented the preliminary results of a survey of radio and $[\text{OIII}]$ images of Seyfert galaxies. About $\sim 50\%$ of our galaxies have unresolved radio emis-

sion (smaller than $0.25''$). Based on conservative assumptions about the area and velocity of a shock in these galaxies, and on the preshock gas density, we calculated the shock and precursor $H\beta$ luminosities for each one of them and compared these values with the observed ones. This showed that, on average, only 15% of the observed $H\beta$ emission can be due to shocks, which is confirmed by the detailed study of two individual galaxies with resolved [OIII] and radio emission (Mrk 79 and NGC 5347). In summary, in most of the cases shocks are not a viable source of ionizing photons for the NLR of Seyfert galaxies.

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